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EVOLUTION OF SURFACE TEXTURE AND CRACKS DURING INJECTION MOLDING OF FIBER-REINFORCED, ADDITIVELY-MANUFACTURED, INJECTION MOLDING INSERTS

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ABSTRACT

This paper investigates the lifetime and surface deterioration of additively-manufactured, injection-moulding inserts. The inserts were produced using digital light processing and were reinforced with oriented short carbon fibers. The inserts were used during injection molding of low-density polyethylene until their failure. The molded products were used to analyse the development of the surface roughness and wear. By enhancing the lifetime of injection-molding inserts, this work contributes to the establishment of additively manufactured inserts in pilot production.

INTRODUCTION

Prior experiments with digital light processing (DLP) or similar technologies and fiber-reinforced photopolymer have been performed showing the possibility of manufacturing parts using this process [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The possibilities of additive manufacturing (AM) for injection molding (IM) were already pointed out earlier in [12, 13, 14, 15]. However, the effect of fibers for the lifetime and surface deterioration of the IM inserts was not yet extensively investigated, although significant advantages at the cost, environmental and efficiency levels can evolve.

The fiber-reinforced polymer (FRP) showed a directional placement of the fibers within the manufactured layers allowing the reinforcement of the insert in two directions [9]. The lifetime of additively manufactured inserts made from photopolymer using DLP is located below those of inserts made from brass or steel as supported by [16, 17]

and, therefore, lifetime in terms of surface quality was the subject of this investigation.

This research contributes to the development of new technologies for injection-molding inserts reducing production costs as well as the environmental impact of prototyping and proof-of-concept manufacturing. It was pointed out by [18] that composite materials for IM inserts made from polymer and copper particles improved the heat conductivity of the inserts by increasing the lifetime of the inserts. This investigation was developed further using short carbon fibers.

METHODS

The IM inserts were produced using DLP from a photopolymer resin with 5 %wt short carbon fiber content equipped with an average diameter of 7.2 μm and an average length of 100 μm extending the research performed by [19] without fiber reinforcement. The layers were placed perpendicular to the expected pressure tensor from the polymer melt from the injection molding process resulting in a fiber placement in the manufacturing layers. The back and sides of the inserts were milled to reduce warpage of the inserts and increase the accuracy of the mold assembly.

The inserts were used during manufacturing with an IM machine injecting low-density polyethylene (LD-PE) at 210 bar maximum injection pressure during a 3 s filling time followed by a 10 s packing time and 10 s cooling phase for the insert in order for the insert to cool down to a temperature of 36 °C. The insert dimensions were 20 x 20 x 2.7 mm³. The total cycle time of the molding was 23 s.

The additively-manufactured insert was built into a multi-functional frame in the IM machine as shown in Figure 1. The LD-PE was injected from

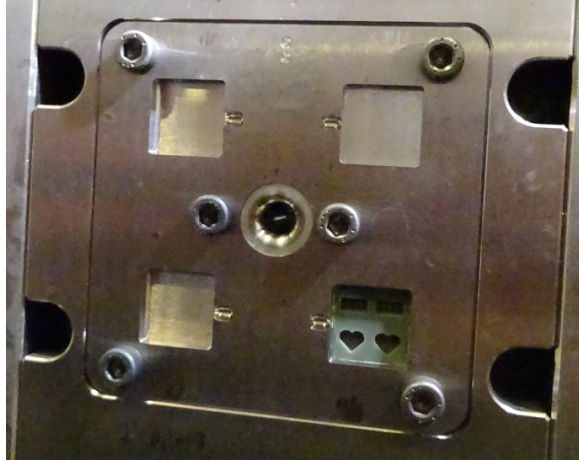


FIGURE 1. Single insert in the IM machine before the first shot.

the reverse side of the insert and through channels guided to the mold. The final part before ejection can be seen in Figure 2.

Tests of the surface structure in terms of roughness were performed using a focus variation 3D microscope system with a vertical resolution of 500 nm and a lateral resolution of 3 μm . The data of the scanned surface was thereafter aligned using global levelling for the inspected areas. The mean roughness was thereafter determined.

Moreover, a scanning electron microscope (SEM) JEOL JSM-5900 was used showing the deterioration of the surface during the molding process. A Dino-Lite Pro AM 4000 digital microscope was used to inspect the surface of the inserts and the parts after the molding process.

RESULTS

During this investigation, the observations in [9] concerning outstanding carbon-fibers at the border of the object were confirmed as the first manufactured parts showed residual carbon fiber material in the upper layer of the part. The outstanding fibers broke off after the first shot and stuck to the produced part. No residuals were found at the second shot and later. The outstanding fibers in the original IM insert are shown in Figure 3. It shall be noted that no fibers are standing perpendicular to the top surface layer.

Surface investigations of produced parts showed cracks of the insert in the μm regime after about 300 shots leading to a change in roughness of the surface of the manufactured part. Compared to other tests on photopolymer inserts without fiber-

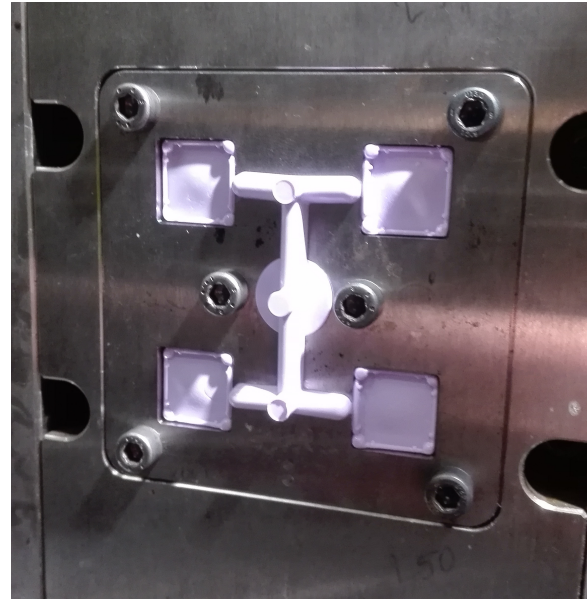


FIGURE 2. PE-LD parts arranged in the IM machine.

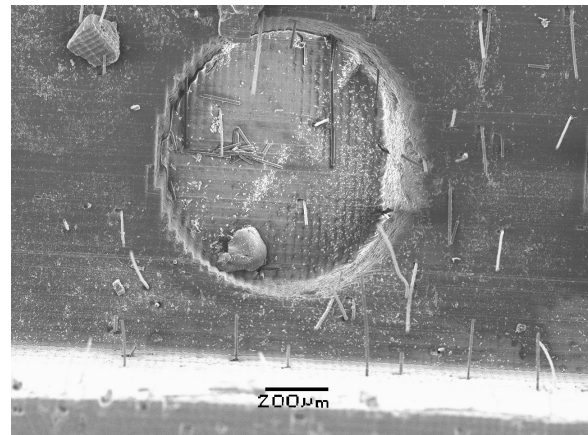


FIGURE 3. Fibers standing out of the produced layers in a SEM investigation confirming the findings in [9]. The image was taken before the first shot. The raster pattern on the surface results from the DLP process and the projector resolution.

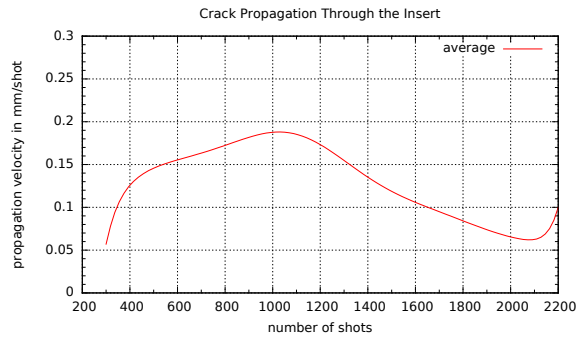


FIGURE 4. Crack propagation velocity over the number of shots (averaged).

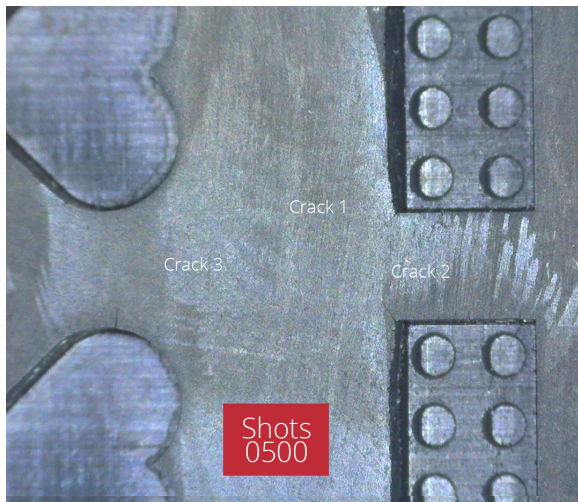


FIGURE 5. Cracks in the insert after shot 500.

reinforcement [19], the enlargement and lengthening of the cracks were significantly reduced allowing a continued production up to several hundred parts.

The crack propagation had an average velocity of 0.145(34) mm/shot after the first sign of the crack until the failure of the part. Figure 4 shows the averaged crack propagation velocity over time showing an increase of the velocity up to 0.19 mm/shot followed by a decrease until failure of the insert. The crack propagation is visualized in Figure 5 to Figure 8 showing the first cracks at shot 500. Crack 2 is blocked by crack 1 after shot 1300 and therefore does not propagate any further. Note also the degradation of the edges as can especially be seen in the round parts on the left side of the figures. Crack 3 also propagates on another level on the lower part after shot 1300.

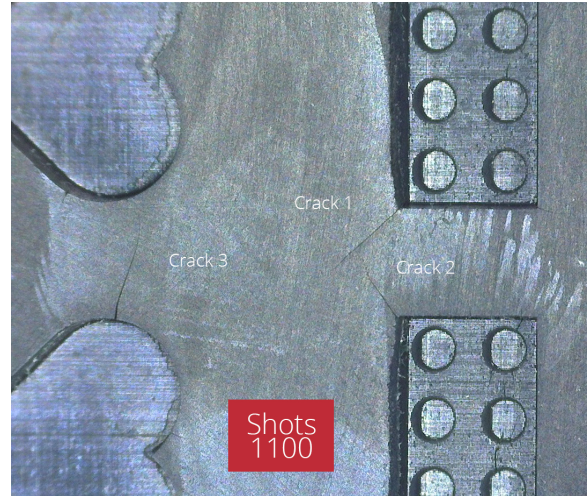


FIGURE 6. Cracks in the insert after shot 1100.

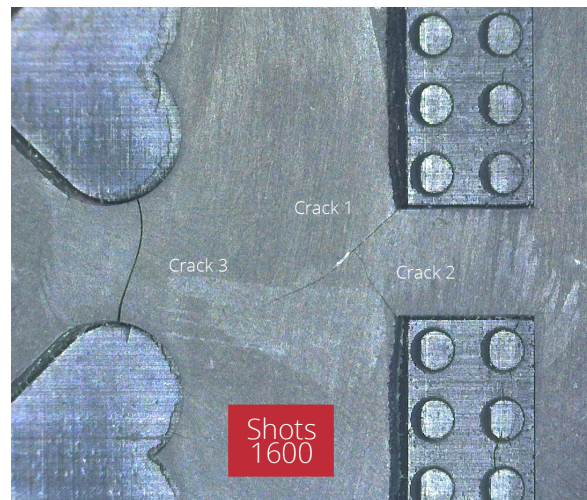


FIGURE 7. Cracks in the insert after shot 1600.

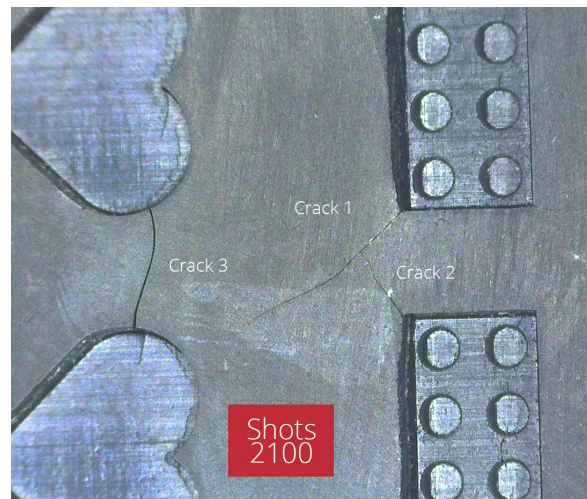


FIGURE 8. Cracks in the insert after shot 2100.

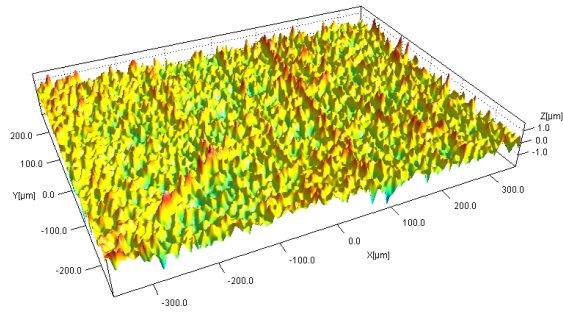


FIGURE 9. Graphical representation of the surface roughness after 10 shots showing the profile under a focal variation 3D-microscope in the middle of the insert.

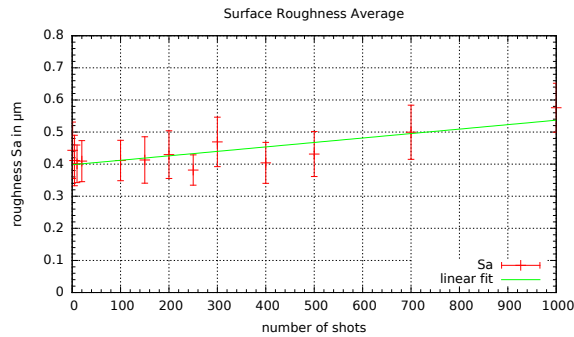


FIGURE 10. Averaged roughness propagation during the first 1000 shots neglecting bigger cracks in the surface.

A graphical representation of the surface of an insert in Figure 9 shows a central surface area with respect to height variations and roughness of the surface. The figure allows conclusions about scratches that were produced during the milling of the insert before the first shot.

Surface roughness despite bigger cracks evolves linearly according to the formula:

$$Sa(\text{shot}) = a + b \cdot \text{shot}$$

$$a = 0.398128 \pm 0.01219$$

$$b = 0.000138742 \pm 3.014 \times 10^{-5}$$

which allows the conclusion that the changes in the general surface roughness can be neglected. The average surface roughness was calculated over 7 inserts with respect to the first 1000 shots (see Figure 10).

The analysis of the surface degradation showed the impact of the fibers within the polymer by re-

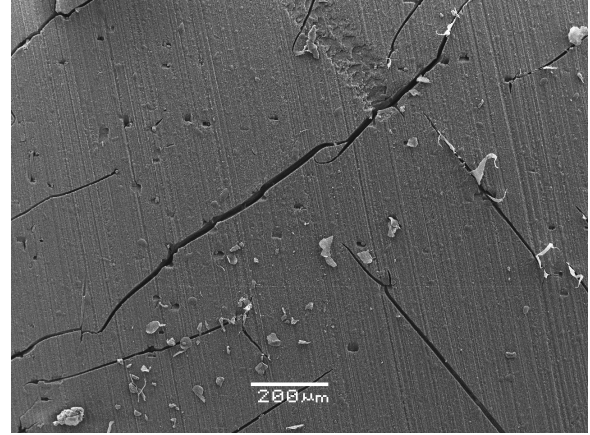


FIGURE 11. Surface cracks in the insert after 2658 shots under an SEM, the debris result from PE-LD stuck in the cracks

ducing the speed of crack propagation within the insert allowing for the running of shots producing parts with a smooth surface appearance although cracks were already present in the insert. The lifetime was investigated by the consideration of cracks on the surface or throughout the entire insert. Cracks producing a flash that was clearly visible without magnification were considered a failure of the insert. It could be shown that the crack propagation was reduced by inserting the fibers in a layer standing orthogonally to the crack orientation. In this way, the fibers contributed better mechanical properties in terms of strength and durability.

Cracks of the insert were reduced to surface cracks as shown in Figure 11 after 2658 shots with low propagation speed and gap size in the range of 1 to 5 μm. Most cracks originated from the edges in the surface of the insert as shown in Figure 12. Those were degrading in such a way that the edges became round as can be seen in Figure 13.

Figure 12 includes parts of the surface protected against thermal and mechanical strain. No cracks evolved in the protected part of the surface and no cracks originated at its border.

The cracks were reproduced in the molded part in the form of flashes for low gap sizes. At larger shot numbers, PE-LD got stuck in the gap as shown in Figure 14 as a detail of Figure 11 and therefore caused severe damage to the produced part. The insert was then characterized as destroyed.

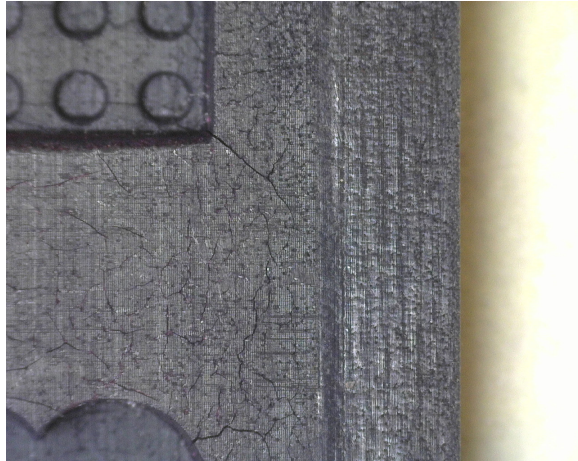


FIGURE 12. Insert surface after 2658 shots showing crack origin at edges as well as parts of the protected surface without cracks.

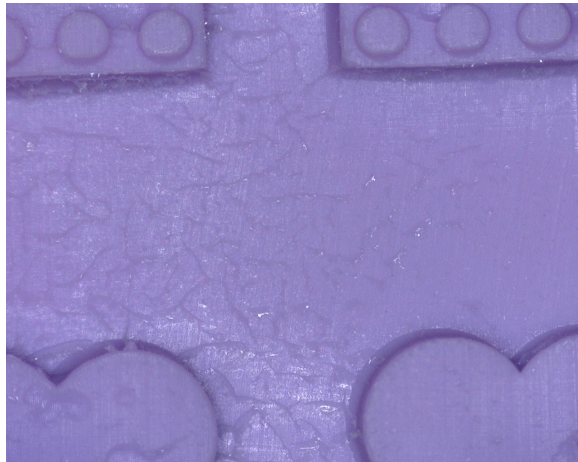


FIGURE 13. Part surface and rounded edges after 2658 shots.

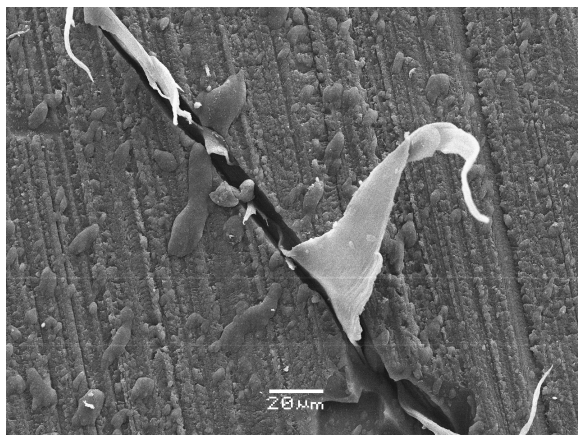


FIGURE 14. Detail of surface degradation with PE-LD material stuck in the crack.

An average number of shots of 2580 was gained using the fiber-reinforced inserts. Compared to the non-fiber-reinforced inserts, the experiments resulted in an increase of the number of shots by 500 %. Crack propagation was reduced to 1.25 % of the velocity in the plain insert.

CONCLUSION

It can be concluded that the lifetime of fiber-reinforced IM inserts could be extended compared to plain IM inserts. The surface wear in terms of mean surface roughness was negligible when inspecting the surface without crack-like features.

Minor racks on the surface appeared early from 300 shots but did not propagate to major cracks, and therefore did not result in fatal failure of the entire insert.

Propagation of major cracks through the entire insert were found to spread slower compared to plain inserts. Thus, it can be concluded that the lifetime of the insert was increased by generating a composite using short carbon fibers.

Additively-manufactured, fiber-reinforced inserts can be considered suitable for pilot production with low part numbers, and therefore are an alternative to more expensive inserts made from brass or steel.

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